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Smouldering combustion as a treatment technology for faeces: Exploring the parameter space

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HIGHLIGHTS

- Faeces mixed with sand can be smouldered in a self-sustaining process.
- This process achieves elimination of biological hazards.
- A robust self-sustaining region for different parameters is identified.
- Is promising as the basis for a new, energy efficient waste treatment approach.

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ABSTRACT

The poor management of human excreta in developing countries is among the most prominent global issues due to its negative impact on public health. This work demonstrates for the first time that self-sustaining smouldering of faeces mixed with sand is a feasible alternative to incineration for rapid destruction of waste. Self-sustaining smouldering requires minimal energy input and pre-drying of faeces compared to incineration. This process ensures the elimination of biological hazards via long residence times (>20 min) at high temperatures (>400 °C). Surrogate faeces which exhibits similar energetic, thermal, and mechanical properties to real faeces are used in this study. The parameters controlling the combustion process including moisture content, airflow rate, and sand-to-faeces ratio are mapped to establish the range of conditions where self-sustaining smouldering of faeces can be achieved. Experiments were conducted within the ranges 0–75% for moisture content, 7–108 g/min for airflow rate and 2.75–11.9 g/g for sand-to-faeces (wet basis) ratio. Preliminary validation of the parameter space is done using real dog faeces. In this work, the parameter space defining the range of conditions where self-sustaining smouldering occurs is mapped. Results show successful self-sustaining smouldering of faeces for moisture contents of up to 60%, airflow ranging from 10 to 100 g/min, and wet sand-to-faeces ratio greater than 3.25. This proof-of-concept for a smouldering reactor to treat human solid waste demonstrates that smouldering of faeces could be the basis for a new, energy efficient waste treatment approach.

1. Introduction

Proper waste management has been identified as one of the global challenges of this century. Incineration and landfilling are the most common methods of waste disposal across the world. Incineration is growing in relative importance [1], being preferred in countries with limited space [2]. Among the most complex waste management processes is the disposal of human excreta. More than 40% of the global population routinely practice open

Abbreviations: DTG, derivative thermogravimetry; MC, moisture content (%); S/F, sand-to-faeces mass ratio (g/g); SS, self-sustaining; TC, thermocouple; TGA, thermogravimetric analysis; T_{peak}, peak temperature recorded in a thermocouple (°C); T_{peak_max}, maximum peak temperature recorded in a thermocouple (°C); U_S, smouldering velocity (cm/min); U_{S_max}, maximum smouldering velocity (cm/min).

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defecation due to lack of adequate sanitation facilities [3]. In developing countries, more than 50% of the urban population have no access to basic sanitation [4]. Poor sanitation is related to many public health problems [5]. Existing approaches to the destruction of human faeces are limited by cost, ineffective sterilization capacity, or practicality [5,6]. Due to the need for rapid destruction and sterilization of the waste, an incineration treatment is often proposed. However, incineration is based on flaming combustion which is associated with high energy losses and continual addition of external fuel. Moreover, the high moisture content (MC) of faeces (75–85%) [7] results in a very low effective calorific value, necessitating substantial pre-drying or the use of supplemental fuel to avoid quenching of the combustion reaction [8,9]. Either of these additional steps makes conventional incineration expensive and energy intensive. Smouldering combustion overcomes these limitations by efficiently transferring the heat generated by the heterogeneous reaction to the unburned fuel, enabling comparable time scales of combustion and heat transfer [10].

To maximise the process efficiency, a one dimensional forward smoulder is used. In forward smouldering, the oxidizer flow and reaction front move in the same direction thereby allowing the heat released by the reaction to be captured by the porous medium and carried forward by the combustion products to preheat the fuel ahead of the front. The energy efficiency of forward smouldering allows for extended quenching limits when compared to the contrasting case of opposed smouldering (in which the airflow is in the opposite direction to the smouldering front propagation) [11]. The reaction rate of smouldering combustion is known to be controlled by the mass flow of oxygen to the smouldering front [11,12].

This paper examines, for the first time, the potential for using smouldering to treat human faeces. This feasibility study is in response to the *Reinvent the Toilet Challenge* launched by the Bill and Melinda Gates Foundation in 2011. The dimensions of the reactor were chosen to accommodate the faeces produced by 10–20 people per day, according to the aims of the foundation. This proof-of-concept for a smouldering reactor to treat human faeces is part of a new integrated, low cost, on-site sanitation system aiming to disinfect human waste within 24 h using minimal resources [13].

1.1. Smouldering combustion

Smouldering combustion is a slow, low-temperature, flameless, oxygen-limited form of combustion driven by the energy released by oxidation of a solid phase fuel [12,14]. It has been studied for a wide range of fuels from a fire safety perspective [15,16], including polyurethane foam [17], biomass [14,18], peat [19], and cotton [20].

Smouldering requires that a fuel be porous as this promotes a high surface area for heat and mass transfer, insulates the reaction front to reduce heat losses, and allows the flow of oxygen to the reaction zone. In the case of liquid or pasty materials (e.g. faeces), smouldering is possible when the fuel is embedded in a porous matrix (e.g. sand). Heat transfer from the reaction to unburned fuel initiates pyrolysis and evaporation before oxidation occurs. Smouldering propagation will occur when the oxidation reaction is sufficiently strong to overcome the heat required for pyrolysis and heat losses. When the reaction is far from its quenching limits, the rate of propagation is directly related to the rate of oxidizer supply to the reaction zone [11]. Close to quenching limits, small perturbations in the fuel characteristics, airflow or heat loses will lead to quenching.

Rein et al. [21] investigated the effect of moisture content, between 46% and 62% (wet base), on the ignition of boreal peat. The critical moisture content for the ignition of this boreal peat was found to be 55%. He [18] also studied the influence of the moisture content and the fuel particle size on the natural downward smouldering of corn stark and other biomass sources. No alterations were observed in the characteristics of the smouldering (temperature, velocity) within the range 0–21% of moisture content. Frandsen [22] showed that the inert porous media and moisture content affect whether sustained smouldering will occur in organic soils. An inorganic content of 81.5% and a moisture content of 33% (wet base) were the ignition limits found. The effect of permeability of the porous media has been studied by Pironi et al. for the smouldering combustion of coal tar [23]. Increasing the grain size was shown to significantly reduce the peak temperature and the rate of propagation up to quenching. Self-sustaining smouldering was not observed using 10 mm gravel in a 15 cm diameter column. That work also examined the influence of water content, where water filled-porosity external to the non-aqueous coal tar fuel resulted in lower peak temperatures and front velocities but did not impede self-sustaining smouldering in the 15 cm tall column. Increased oxygen mass flux has been shown to result in an increase in the smoulder spread rate [17,23–25]. Smouldering temperatures and quenching limits were demonstrated to be a complex function of oxygen supply, convective heat transfer and the thermal properties of the porous medium [17].

1.2. Application of smouldering as a treatment for faeces

The high moisture content of faeces makes this fuel challenging due to its low calorific content ($\sim$4 kJ/g (considering moisture content 75%) compared to $\sim$30 kJ/g for coal [26] and to $\sim$20 kJ/g for wood [27]). Little is known about the smouldering characteristics of this fuel. A porous matrix is created with the necessary heat retention and air permeability properties for smouldering combustion by mixing the faeces with sand. Sand is used here because it is a low cost commodity in developing countries and because it has been identified as an effective agent for increasing the porosity of fuels for application to smouldering treatments [24].

To manage the regulatory challenges of working with real faeces and to control the experimental variables, a non-hazardous surrogate faeces is used for the majority of the experiments. Forty-seven experiments are carried out with the surrogate faeces to determine the limits of self-sustaining smouldering across a range of moisture contents, sand to faeces mass ratios (S/F), injected airflow rates, and amount of faeces (packed height). The results include peak temperatures and smouldering velocities as a function of these variables. Eleven experiments with dog faeces are also conducted to confirm consistent results between the surrogate and real faeces. Dog faeces were selected because it contains minimal human pathogens. Overall, this work serves as an initial investigation into the feasibility of applying this approach in a waste treatment system.

2. Experimental procedure

Upwards forward smouldering combustion experiments are done within a purpose-built reactor illustrated in Fig. 1. The column is cylindrical (16 cm inner diameter, 100 cm height), placed over a stainless steel base which houses a spiral-coiled heater (Incoloy-sheathed, 2.2×4.2 mm cross-section) and air diffuser. The air diffuser consists of a ring-shaped tube perforated with six pairs of diametrically opposite holes. These components are covered with layers of coarse gravel, fine gravel, and sand to ensure uniform airflow. The heater is embedded beneath the upper surface of the sand layer. The column is then filled with the sand–faeces mixture up to the desired height before a final 2 cm layer of clean sand is placed atop.

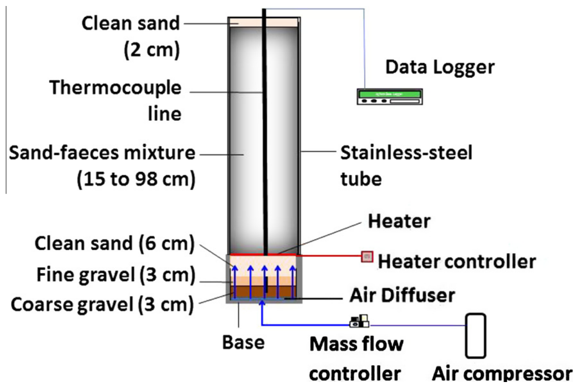

Fig. 1. Schematic representation of the reactor used in experiments.

Table 1
Surrogate faeces composition.

Ingredient	Function	Energy (kJ/g)	Dry weight (%)
Propylene glycol	Water retention	26.1	20
Baker's yeast	Bacterial debris proxy	18.6	10
Peanut oil	Fat proxy	34.0	5
Miso paste[a]	Proteins proxy	16.8	30
Cotton	Cellulose, fiber	16.7	15
Psyllium husk powder	Dietary fiber	8.0	15
Dicalcium phosphate	Minerals	0	5
Water[b]	Moisture	0	0

[a] Miso paste has a moisture content of approximately 50%.
[b] Water is added to every formulation to meet the desired moisture content.

A surrogate faeces recipe based on [28] is used, and detailed in Table 1. Energy content, water holding capacity, and mechanical consistency were matched between the surrogate and real faeces. A fresh batch of surrogate faeces is prepared prior to each test and mixed with sand (0.6–1.2 mm grain size, 1700 kg/m^3 bulk density) using a food mixer. The energy content of each ingredient is listed in Table 1. This gives an approximate heat of combustion for the surrogate of 17.5 kJ/g (dry basis), similar to the 17.6–25.1 kJ/g (dry basis) [29–31] for real faeces. Heat of combustion is used here to demonstrate a qualitative equivalence, although it is not the energy released during smouldering because of the different reaction pathways that occur during smouldering combustion. Since the surrogate heat of combustion is at the low end of the expected range for real faeces, this suggests that the surrogate provides a conservative estimate of the robustness of the process.

The propagation of the smouldering reaction is monitored by 24 thermocouples (TC) positioned along the central axis of the tube. The first five TCs (TC1 to TC5) are spaced at 1 cm intervals, with TC1 located 2 cm from the heater. The remaining thermocouples (TC6 to TC24) are spaced at 5 cm intervals. Temperatures are recorded in 5 s intervals.

Initial heating of the column is achieved by ramping the heater's power from 200 W to 600 W in 100 W increments every 10 min. Once TC1 (2 cm from the heater) reaches 400 °C, the smouldering reaction is initiated by the injection of air using a differential pressure mass flow controller (Cole Parmer 32907-75). The heater is turned off once the temperature at TC1 peaks. The duration of preheating ranges from 61 min to 136 min, depending on the moisture content and sand-to-faeces ratio. This procedure and configuration (one-dimensional, forced, forward smouldering) yields a robust, repeatable ignition across a wide range of conditions [23,32]. Table 2 summarizes the conditions of the experiments performed. The sand-to-faeces (S/F) ratio listed in the table refers to mass of sand relative to mass of wet faeces at the described moisture content.

Eleven preliminary experiments with dog faeces defined in Table 3 are used to validate the parameter space mapped for the surrogate. The dog faeces samples were collected from the Veterinary Clinic at University of Queensland, and stored in a conventional freezer until there was enough material for the experiments. Before the experiments, the dog faeces were thawed overnight at room temperature. To adjust the moisture content to the desired value, the samples were dried in an oven (Thermoline TSO-80W) at 30–60 °C, or water was added to the sand–faeces mixture. Both surrogate and dog faeces were characterized by thermogravimetric analysis (TGA). The TGA experiments were carried out in a STA600 from Perkin Elmer, from 30 °C to 900 °C under nitrogen and air flow. The heating rate used was 10 °C/min at a gas flow rate of 20 mL/min.

3. Results and discussion

3.1. Base cases

Temperature histories in the reactor for a select number of experiments are shown in Figs. 2a, 3a and 4a. Corresponding spatial temperature distributions at select times are presented in Figs. 2b, 3b and 4b. Each thermocouple reaches a maximum temperature that is defined as T_{peak}. The smouldering velocity U_S is calculated from the time lapse of the steepest slope in the temperature history of two consecutive thermocouples and the distance between them. The greatest values of T_{peak} and U_S within an experiment are denoted by T_{peak_max} and U_{S_max} respectively. Normalized peak temperatures (T_{peak}/T_{peak_max}) for each TC and the normalized smouldering velocity (U_S/U_{S_max}) are shown in Figs. 2b, 3b and 4b.

The repeatability of the experiments was studied by performing three experiments (A, B and C) under exactly the same experimental conditions (70% MC, 65 cm pack height, 3.75 g/g S/F and airflow of 108 g/min). All three experiments resulted similar and quenched at the same position, between 21 cm (TC8) and 26 cm (TC9). Considering only the smouldering zone, the average T_{peak} and U_S were calculated and are shown in Table 4. Moreover, every experiment was repeated at least twice. The difference in smouldering temperatures and velocities for experiments in robust conditions is less than 10%. According to these values, it is possible to assume that the observed variability gives a reasonable estimate of the expected variability of repeats, and thus allows differences between experiments to be attributed to the controlling variable rather than random noise.

Fig. 2a presents the example of a self-sustaining (SS) experiment. The preheating period lasted approximately 100 min and is characterized by a gradual increase in temperature and a plateau at 100 °C which corresponds to water evaporation. As the distance from the heater increases, the duration of this plateau increases as more energy is consumed in the evaporation of the additional water that has condensed in the cooler portion ahead of the smouldering front.

When the air flow is initiated, the location closest to the heater experiences a sharp increase in temperature up to a peak >600 °C as rapid exothermic oxidation occurs. The adjacent TCs experience a temperature increase due to the convective heat transfer from the reaction zone to the virgin material ahead. From TC6 (11 cm) upwards reveals convective heating of the sand–faeces mixture by the hot post-combustion gases. This is characterized by a temperature plateau at an almost constant value of approximately 70 °C, which has also been observed during smouldering of polyurethane foam [17]. In this zone, as the reaction front approaches, only a minor plateau is observed at temperatures slightly over 100 °C indicating that the heat flux from the combustion zone is

Table 2
Experiments conducted with surrogate faeces.

	Experiment	Height (cm)	MC (%)	S/F (g/g)	Airflow (g/min)	Self-sustainable
Moisture content vs Height in column	1	16	75	3.75	108	Yes
	2	20	79	3.75	108	No
	3	22	55	3.75	108	Yes
	4	22	75	3.75	108	Yes
	5	55	55	3.75	108	Yes
	6	55	60	3.75	108	Yes
	7	55	65	3.75	108	Yes
	8	55	70	3.75	108	Yes
	9	55	75	3.75	108	No
	10	67	70	3.75	108	No
	11	70	70	3.75	108	No
	12	98	60	3.75	108	Yes
	13	98	65	3.75	108	Yes
	14	98	70	3.75	108	No
	15	98	75	3.75	108	No
Moisture content vs Sand-to-faeces ratio	16	98	65	2.75	108	No
	17	98	60	3.00	108	No
	18	98	65	3.00	108	No
	19	98	60	3.25	108	Yes
	20	98	65	3.25	108	No
	21	98	60	3.50	108	Yes
	22	98	65	3.50	108	No
	12	98	60	3.75	108	Yes
	13	98	65	3.75	108	Yes
	14	98	70	3.75	108	No
	15	98	75	3.75	108	No
	23	98	60	4.00	108	Yes
	24	98	65	4.00	108	Yes
	25	98	70	4.00	108	No
	26	98	70	4.25	108	Yes
	27	98	65	11.9	108	Yes
Airflow rate vs Sand-to-faeces ratio	28	55	65	2.00	108	No
	29	55	65	2.25	108	No
	30	55	65	2.50	108	No
	31	55	65	2.75	14	No
	32	55	65	2.75	30	No
	33	55	65	2.75	54	No
	34	55	65	2.75	108	Yes
	35	55	65	3.00	30	No
	36	55	65	3.00	80	Yes
	37	55	65	3.25	19	No
	38	55	65	3.25	30	No
	39	55	65	3.25	108	Yes
	40	55	65	3.50	41	No
	41	55	65	3.50	52	Yes
	42	55	65	3.50	108	Yes
	43	55	65	3.75	7	No
	44	55	65	3.75	14	Yes
	45	55	65	3.75	22	Yes
	46	55	65	3.75	42	Yes
	7	55	65	3.75	108	Yes
	47	55	65	11.9	108	Yes

Table 3
Experiments conducted with dog faeces.

Experiment	Height (cm)	MC (%)	S/F (g/g)	Airflow (g/min)	Self-sustainable	Comments
D1	22	75	3.75	108	Yes	Validate the parameter space MC vs height showed in Fig. 6b for surrogate faeces
D2	22	78	3.75	108	No	
D3	55	60	3.75	108	Yes	
D4	55	68	3.75	108	No	
D5	55	75	3.75	108	No	
D6	98	60	3.75	108	Yes	
D7	98	60	3.25	30	Yes	Validate parameter space for 98-cm experiments
D8	98	62	3.50	108	No	
D9	98	69	4.00	108	No	Explore the parameter space MC vs S/F showed in Fig. 6b for surrogate faeces
D10	98	72	4.25	108	No	
D11	98	75	4.65	108	No	

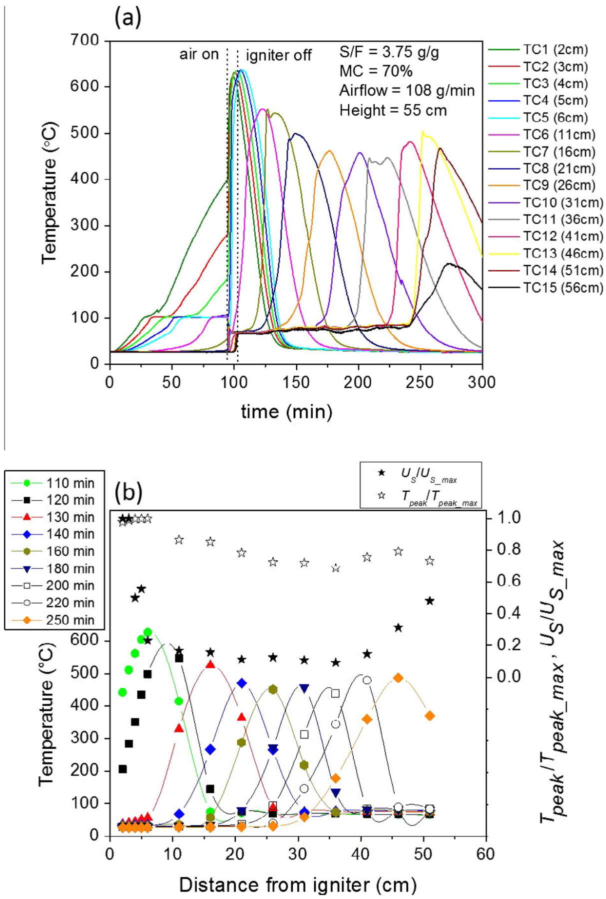

Fig. 2. (a) Temperature histories from a self-sustaining smouldering experiment with surrogate faeces (70% MC, 3.75 g/g S/F, 108 g/min airflow, 55 cm pack height). (b) Spatial temperature distributions with normalized peak temperatures and smouldering velocities as a function of the distance.

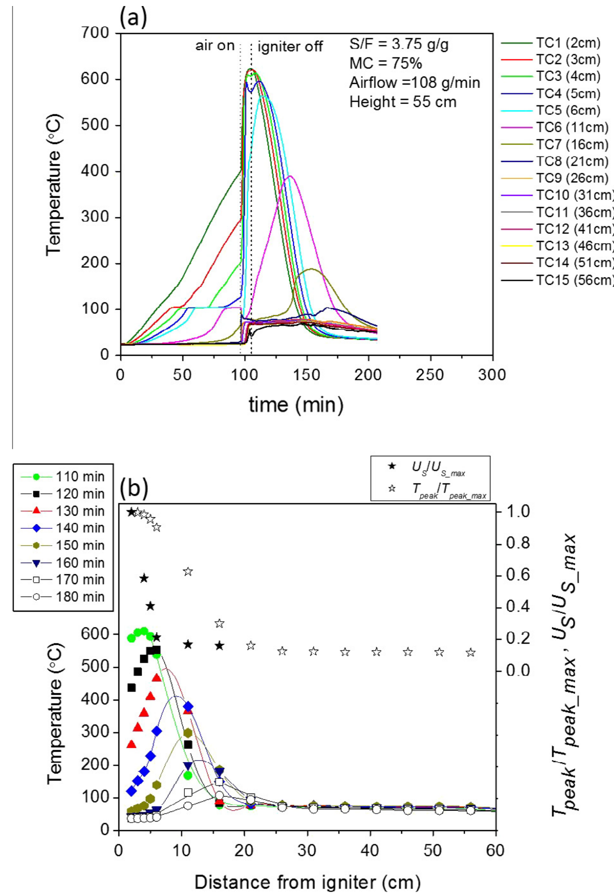

Fig. 3. (a) Temperature histories from a non-self-sustaining smouldering experiment with surrogate faeces (75% MC, 3.75 g/g S/F, 108 g/min airflow, 55 cm pack height). (b) Spatial temperature distributions with normalized peak temperatures and smouldering velocities as a function of the distance.

sufficiently large to dry the mixture ahead. The sand–faeces mixture is thus pre-dried ahead of the smouldering front's arrival. As the fuel is consumed and the reaction at that location stops, the temperature falls as it is cooled by incoming air. The repetition of non-diminishing temperature peaks throughout the reactor is indicative of a self-sustaining smouldering reaction [17], as observed in Fig. 2b.

Fig. 2b illustrates that the smoulder velocity and peak temperature is elevated in the first 5 cm above the heater; this boundary effect likely occurs because propagation is through dried, pre-heated material. In the bulk of the column, the velocity and peak temperature are relatively constant. Also at the upper end of the material, an increase in the smoulder velocity and peak temperature is observed. In this case, it probably occurs because the thermal conductivity of the clean sand is lower than that of the mixture, acting like an insulator and favouring the energy balance at the reaction zone. Given the exponential nature of the reaction rates, the increased heat release rate leads to acceleration of the propagation front. This has been observed for coal tar/sand mixtures [32] and polyurethane foam [33]. TC15 showed a lower peak temperature because it is embedded in the clean sand.

A non-self-sustaining (non-SS) experiment is presented in Fig. 3. The experimental conditions are the same than those of the experiment presented in Fig. 2 experiment, except for a MC of 75% instead of 70%. Similar to the previous experiment, peak temperatures >600 °C are registered near the heater. However, these temperatures systematically decrease beyond TC1 and with increasing rapidity after TC5 (6 cm) (Fig. 3b). Fig. 3a shows that through the ignition period the pre-dried region extends to TC4, beyond which moisture is evaporating as evidenced by the sudden decrease in temperature of TC5 and TC6 when the airflow starts ($t \sim 90$ min). While smouldering ignition occurs, it is most likely that the reaction cannot overcome the heat sink of so much water and does not propagate. Fig. 3b illustrates that the reaction fails to show any signs of exothermicity beyond 6 cm, where propagation ceases and the maximum temperature drops drastically. This case deviates from the former as soon as the reaction leaves the region influenced by the igniter.

Fig. 4 shows the data of an experiment with same conditions than the SS (Fig. 2), but with 70 cm length packed with the sand–faeces mixture instead of 55 cm. In this case, the temperature profiles up to approximately 20 cm are similar to the SS experiment, with temperature peaks >500 °C. However, after 21 cm (TC8) there is a steady decrease in peak temperatures and smouldering velocity and the reaction quenches. Close to 150 min, the temperature history of TC8 shows brief plateaus between 300 °C and 500 °C that can be attributed to pyrolysis of the fuel [17], consistent with thermogravimetric analysis (TGA). At the same time, the temperature 5 cm ahead (26 cm, TC9) is still below 100 °C, showing that the mixture is being dried. Contrary to the SS experiment, the drying ahead of the front is very slow; nevertheless the reaction reaches TC9 when the mixture is almost dry because only a minor plateau is observed at 100 °C. After this plateau, the temperature increases faster as the fuel is consumed, however the peak temperature is only 300 °C. The reaction quenches after 26 cm (TC9) and no signs of exothermicity are observed above this

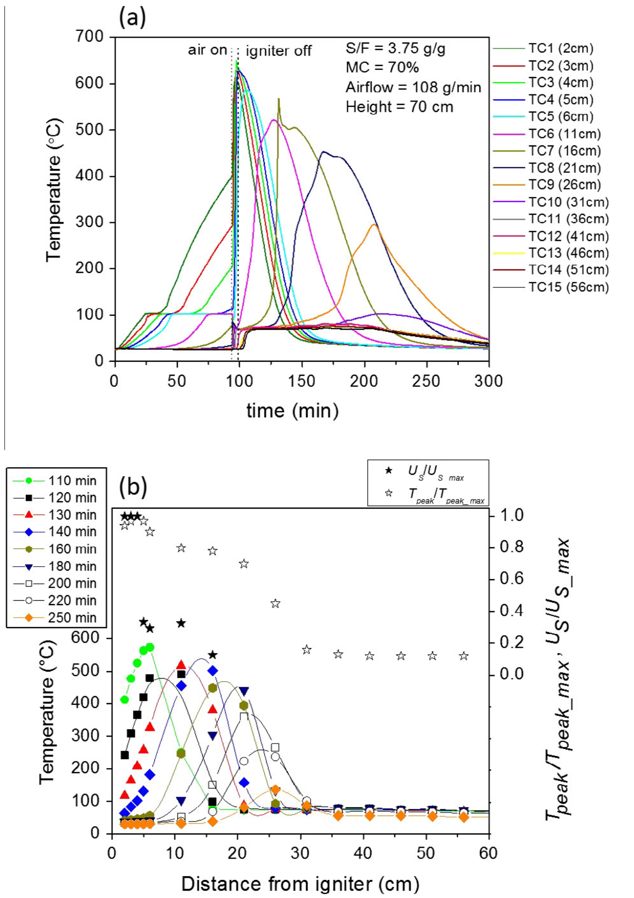

Fig. 4. (a) Temperature histories from a non-self-sustaining smouldering experiment with surrogate faeces (70% MC, 3.75 g/g S/F, 108 g/min airflow, 70 cm pack height). (b) Spatial temperature distributions with normalized peak temperatures and smouldering velocities as a function of the distance.

Table 4
Average peak temperature (T_{peak}) and smouldering velocity (U_S) for three experiments (A, B and C) under the same experimental conditions (70% MC, 65 cm pack height, 3.75 g/g S/F and airflow of 108 g/min).

Experiment	A	B	C
Average T_{peak} (°C)	576 ± 45	529 ± 39	538 ± 46
Average U_S (cm/min)	0.22 ± 0.07	0.25 ± 0.03	0.17 ± 0.02

location. The peak temperature at 31 cm barely reaches 100 °C, indicating that the mixture was wet. Moreover, Fig. 4b shows that after 180 min, the drying front does not progress beyond 30 cm. The smouldering velocity for this and the SS experiment are almost identical up to approximately 21 cm where a sudden deviation initiates quenching in the longer sample. A progressive deviation from the SS conditions would have indicated weakening of the reaction due to a differential accumulation of moisture linked to the column height. The sudden departure from the SS temperatures is best interpreted as the condition where water accumulation reaches a critical condition that enables its downward migration. This is supported by the presence of furrows (i.e., flow pathways) observed in the sand–faeces mixture after excavation of non-SS experiments. This critical condition will be a function of the height of the water column above the reaction and accumulated MC.

In a similar experiment (same experimental conditions but a column with i.d. = 21 cm) the moisture redistribution after the experiment was quantified (using a Mettler Toledo HB43-S Moisture Analyser), at different heights. In this case, the reaction quenched at 10 cm. The moisture content was analysed above that region, and is presented in Fig. 5. Although, the portion of sand–faeces close to the smouldering front (13–15 cm) was drier than the original mixture, after 20 cm water is seen to concentrate to values above the original moisture content (which is indicated by a dashed line).

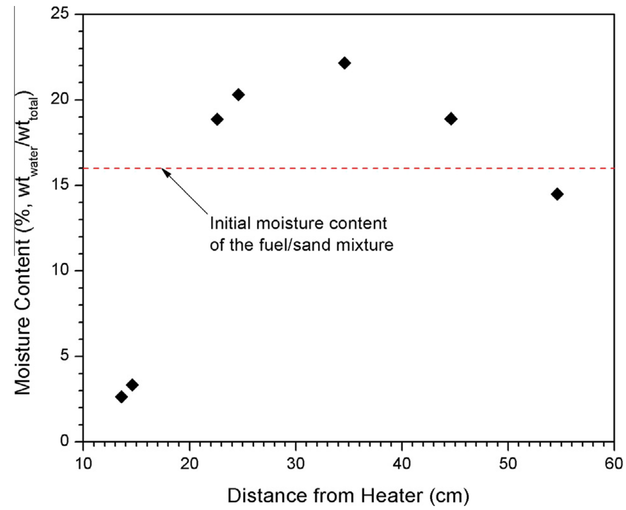

Fig. 5. Moisture distribution of the sand–fuel mixture above the reaction zone for a non-self-sustaining test with 3.75 S/F and 75% MC in a 21 cm inner diameter reactor with thermocouples spaced at 3.5 cm intervals.

3.2. Mapping the parameter space

The parameter space defining the range of conditions where self-sustaining smouldering occurs is mapped in Fig. 6, showing the interdependent relationships between moisture content and pack height, moisture content and sand-to-faeces ratio, and airflow and sand-to-fuel ratio. Fifteen experiments were carried out to study the influence of pack height on the range of moisture content where self-sustaining smouldering occurs (Fig. 6a). In these experiments the pack height and moisture content were varied between 15 cm and 98 cm, and 55% and 78%, respectively. Other experimental parameters remained constant at 3.75 g/g for sand-to-faeces ratio and 108 g/min for airflow rate. Fig. 6a shows that the maximum moisture content permitting self-sustaining smouldering is a function of pack height. This may be attributed to a downward migration of moisture due to increased hydrostatic pressure, aided by increased recondensation of water with taller sand–faeces packs. Water migration is characterized by a progressive decrease in the temperature profile. An example of this is the experiment previously shown in Fig. 3a and b. The maximum moisture content found for a SS experiment was 75% using a 20 cm pack height. This result has significant practical implications, suggesting that self-sustaining treatment of faeces may be possible without the energy intensive pre-treatment step of partial drying.

The influence of the sand-to-faeces ratio on the moisture content range where self-sustained smouldering occurs was studied with 16 experiments. For these experiments, fixed experimental conditions 98 cm pack height and airflow of 108 g/min were chosen. Fig. 6b shows experiments were the moisture content was varied form 60% to 75%, while the S/F ratio was between 2.75 and 4.25 g/g. The maximum moisture content yielding self-sustaining smouldering is a function of the sand-to-faeces ratio. Results showed that for every moisture content <70% there is a limit of S/F ratio, and this limit increases when the moisture content

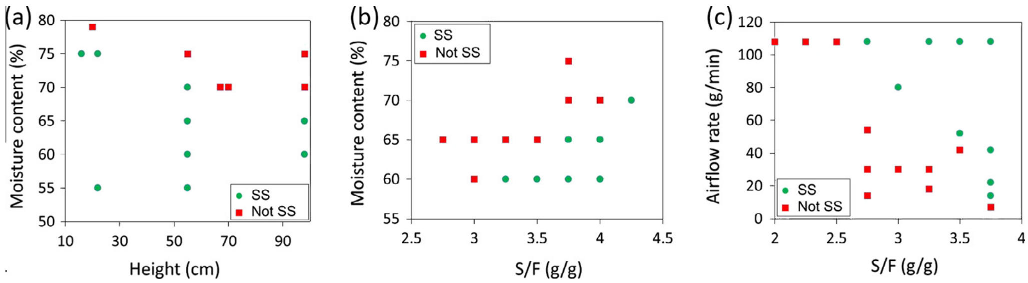

Fig. 6. Parameter space outlining the range of conditions yielding self-sustaining smouldering. (a) Moisture content versus height of sand–fuel mixture at constant 3.75 S/F and 108 g/min airflow. (b) Moisture content versus sand-to-fuel ratio at constant 98 cm pack height and 108 g/min airflow. (c) Airflow versus sand-to-fuel ratio at constant 50 cm pack height and 65% MC.

increases. The increment in S/F reduces the total amount of water in the column; and hence this allows for extended quenching limits of MC. It is hypothesized that higher sand-to-faeces ratios increase the capacity for recondensed moisture ahead of the smouldering front, preventing downward migration of water at high moisture contents. On the other hand, higher S/F ratios reduce the amount of fuel per unit volume, and therefore the energy available for propagation of the reaction. This observation suggests that there is a high limit of S/F ratio; however this limit was not studied here. Experiment 27 (Table 2, not presented in Fig. 6b) showed that SS smouldering is possible at 11.9 g/g S/F ratio. Under these conditions, the maximum moisture content allowing self-sustaining smouldering is at 70% moisture content, when S/F ratio is 4.25 g/g.

The self-sustaining parameter space considering airflow rate and S/F ratio was studied with 21 experiments at 65% moisture content and 55 cm of fuel pack height. Fig. 6c shows experiments were the airflow rate was varied from 7 to 108 g/min, while the S/F ratio from 2.00 to 3.75 g/g. Self-sustaining experiment 47 (Table 2), with 11.9 g/g S/F ratio and 108 g/min of airflow rate, is not presented in Fig. 6c for better representation. The minimum airflow allowing for self-sustaining smouldering is a function of sand-to-faeces ratio, as seen in Fig. 6c. Higher airflow rates increases the oxygen gradient from the bulk porosity to the fuel surface [34]. Additionally, higher sand-to-faeces ratios increase the interfacial area between the fuel and air; allowing for greater diffusion of oxygen to the fuel. These effects allow reduced airflow when S/F ratio is increased. Under these conditions, results showed that is possible to smoulder with an airflow rate of 14 g/min (darcy flux of 0.74 cm/s) when S/F is at least 3.75 g/g. Pironi et al. [23] found that the smouldering reaction of coal tar and crude oil (both dry) is self-sustainable at least down to an air darcy flux of 0.5 cm/s. Although the influence of the moisture content on the airflow rate limit was not studied, it is expected that faeces with lower moisture content could be smouldered with even lower airflow rates because of the reduced heat sinks and more fuel per mass of sand for a given S/F ratio.

The long residence times (>20 min) at high temperatures (>400 °C) during smouldering combustion are enough to achieve sterilization [12]. This is a critical result in the context of reinventing the toilet, since elimination of all pathogens within 24 h is a key objective. Organic matter is destroyed by the smouldering reaction, leaving dry sand. Upon first use, this sand was typically

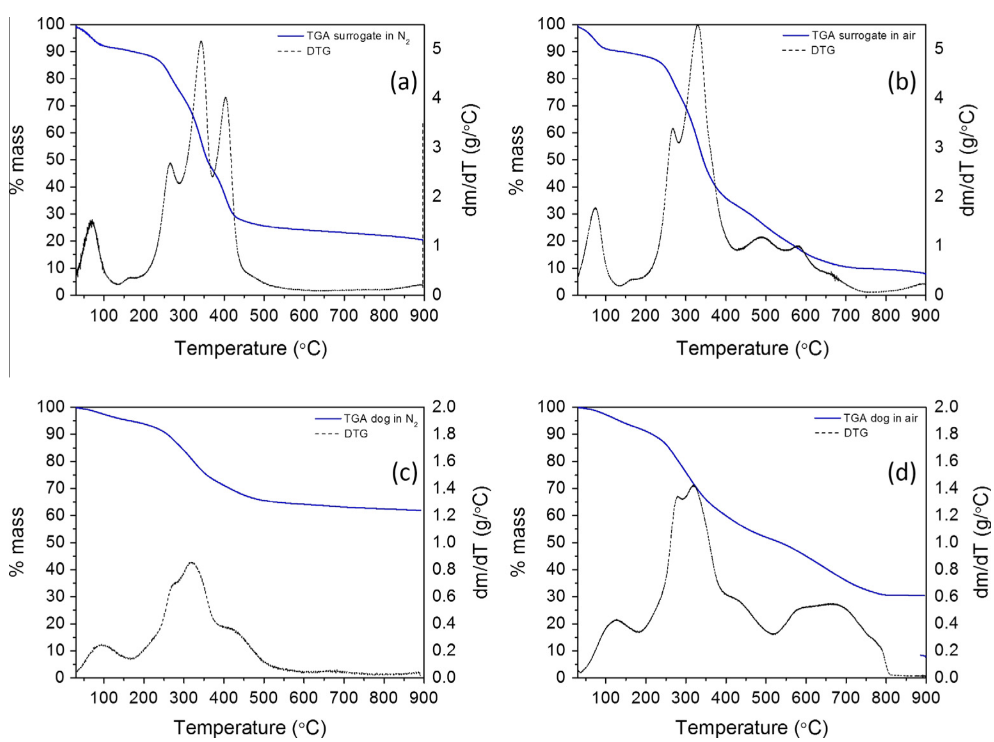

Fig. 7. Thermogravimetric analysis (TGA) and its first derivative (DTG) with a heating rate of 10 °C/min and a gas flow rate of 20 mL/min of: (a) surrogate faeces in nitrogen atmosphere, (b) surrogate faeces in air atmosphere, (c) dog faeces in nitrogen atmosphere and (d) dog faeces in air atmosphere.

left with red colouration attributed to the oxidation of iron species [24]. Inorganics in the fuel, which do not combust, are retained as ash. The mass of retained ash is in agreement with the mass of inorganics in the fuel (here 5%, Table 1). The sterilized sand is ideal for recycling through the process; reusing one batch of sand 5 times revealed no measurable change in the self-sustaining smouldering reaction, peak temperatures, or front velocities.

3.3. Dog faeces validation

The surrogate faeces formula is shown to be a suitable proxy for real faeces by TGA and its first derivative (DTG) in nitrogen and air presented in Fig. 7a–d. The experiments were carried out with previous dried samples. However, a small amount of water was detected which corresponds to atmospheric water absorbed during manipulation. This is observed as a mass loss peak between 50 °C and 100 °C in the four TGA experiments. Pyrolysis is seen in nitrogen DTG between 200 °C and 550 °C for both surrogate (Fig. 7a) and faeces (Fig. 7c). In both cases, the peaks observed in the range of 200–500 °C correspond to the decomposition of the different compounds present in the faeces (yeast, fibres, oil). Combustion in air extends beyond the pyrolysis peaks between 200 °C and 700 °C for the surrogate (Fig. 7b) and 200 °C and 800 °C for dog faeces (Fig. 7d). Mass loses over 500 °C are attributed to the combustion of the vegetable fibres and microorganism debris. It was observed that combustion of psyllium husks can be extended up to 600 °C, while yeast up to 800 °C (data not shown). The extended mass loss up to 800 °C in the TGA/DTG of dog faeces under air atmosphere would indicate a high content of bacteria.

Experiments with dog faeces are defined in Table 3. Experiments D1 to D8 validate the parameter space in Fig. 6a. Dog faeces with a 75–78% MC (D1 and D2) are shown to have roughly the same moisture content limit as the surrogate with 22 cm pack height. At 55 cm, the moisture content limit is between 60% MC and 68% MC for dog faeces and roughly 70% for surrogate (D3 to D5). At 98 cm, dog faeces with 60% MC yields self-sustained smouldering (D6). A lower airflow rate (30 g/min) and S/F ratio (3.25 g/g), while maintaining 60% MC and 98 cm pack height (D7), also results in self-sustaining smouldering, in agreement with the surrogate parameter space. Experiments D9 to D11 explore the parameter space mapped in Fig. 6b by increasing moisture content and sand-to-fuel ratio along the divide of parameters yielding self-sustaining and non-self-sustaining smouldering. All three of the dog faeces experiments were non-self-sustaining, in agreement with the trend observed for the surrogate.

4. Conclusions

A parameter space has been mapped for conditions yielding self-sustaining smouldering of surrogate faeces mixed with sand by varying moisture content, sand–faeces pack height, airflow rate, and sand-to-faeces ratio. Smouldering velocity and temperature depend on these parameters. Self-sustaining smouldering is demonstrated to be possible under a wide range of conditions, and this work suggests that these parameters can be adjusted to control the rate of mass destruction and remain within this self-sustaining operating window. Preliminary validation of the parameter space with dog faeces suggests that the surrogate is a suitable proxy for faeces, although further study could alleviate uncertainties due to the variability of faeces composition.

This technique offers a potentially robust and energy-efficient approach to the destruction and disinfection of solid waste streams with a wide range of moisture contents, including higher than possible with flaming combustion. The long residence times at high temperatures ensure the elimination of biological hazards, ideal for the treatment of solid human waste. It is acknowledged that this is an initial study and confirmation with human faeces is needed. Engineering issues with implementing the technology in a practical manner remain to be explored. It is noted that this approach could be applied to other low-energy waste streams. In addition, such systems provide significant potential for energy recovery (e.g., from the emissions, from the hot sand).

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